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Radiation Errors in Air Ducts Under Nonisothermal Conditions Using Thermocouples, Thermistors, And a Resistance Thermometer

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Radiation Errors in Air Ducts Under Nonisothermal Conditions Using Thermocouples, Thermistors, and A Resistance Thermometer

Joseph C. Davis

Building Research Division
Institute for Applied Technology
National Bureau of Standards
Washington, D.C. 20234

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Radiation Errors in Air Ducts Under Nonisothermal Conditions Using Thermocouples, Thermistors, and a Resistance Thermometer

Joseph C. Davis*

Studies were made to determine the radiation error in temperature measurements made with thermocouples, thermistors, and a resistance thermometer in moving air at velocities ranging from 300 to 1300 fpm when the temperature of the duct wall surrounding the air stream was from 0 to 50 deg F higher than that of the air in the center of the duct. To eliminate all but the variable under study, conduction errors were minimized to a point where they were almost nonexistent by using Chromel P–constantan thermocouple wire and by employing other techniques. Radiation effects were studied when the probe housing the three types of temperature sensors was unshielded and again when it was shielded. The studies showed that when the sensors were unshielded and the temperature difference between the duct wall and the air was 50 deg F (28 K, approximately), the error in the sensors was about 3.8 deg F (2.1 K) for an air velocity of 300 fpm (1.5 m/s) and 1.0 deg F (0.6 K) for an air velocity of 1300 fpm (6.6 m/s). When the sensors were shielded, the error was about 0.2 deg F (0.1 K) for 300 and 500 fpm velocities and the same duct wall air-temperature difference. Tests were not performed at 1300 fpm with the sensors shielded because theory indicated that radiation error would be negligible at this velocity. Under the test conditions that prevail in the testing of air conditioners and heat pumps in laboratories, it should be possible to reduce the error in temperature measurement of the moving air to about 0.2 deg F (0.1 K) by a suitable combination of air mixers, duct insulation, radiation shields, and calibration techniques.

Key words: Conduction error; radiation error; resistance thermometer; temperature measurement; thermistor; thermocouple.

*Present address: 4534—47th St., N.W., Washington, D.C. 20016.

1. Introduction

Accuracy of measurement of the temperature of moving air depends, among other things, on the effectiveness of precautions taken to minimize conduction and radiation errors. It is known that in the determination of the thermodynamic properties of moving air, these errors can be significant at air velocities below 1000 fpm and when the temperature of the surroundings, such as a duct wall bordering a stream of moving air, is 20 deg F different from that of the air at the position of the sensor. However, the literature does not show much information on the magnitude of error at these velocities and temperature differences.

The error in determining the capacity of an air conditioner or a heat pump in a laboratory can be as high as 5 percent if the error in the temperature measurement from these sources is neglected, even though the temperature difference between the air and the duct wall may not exceed 6 deg F. Similarly, the measurement of the moisture generation capacity of a humidifier can be as much as 10 percent in error if corrections are not made to the observed temperature.

In a previous paper by Davis, Faison, and Achenbach [1][1] showing the results of the study of the errors of thermocouples, thermistors, and mercury-in-glass thermometers used in moving air, and where the temperature of the duct wall was essentially the same as that of the sensors, it was shown that the principal errors under those conditions were due to change in performance of the sensors between calibrations, and to false readings due to thermal lag of the sensors. Other smaller sources of error found in the study were self-heating of the thermistors, parallax difficulties in reading the mercury-in-glass thermometers, orientation of the thermometers, and impact error due to the energy of motion of the air stream.

Shielded and unshielded temperature sensors are widely recommended in various standard test pro-

[1] Figures in brackets indicate the literature references on page 12.

cedures for air conditioning, heating, and refrigerating equipment for indicating the temperature of moving air in ducts under conditions where the temperature of the duct wall may be significantly different from the air temperature in the duct. This study was designed to evaluate the magnitudes of the radiation errors for three common types of sensors, used with or without shielding, for a range of air velocities and a range of temperature differences between the duct wall and the moving air, and to indicate application techniques that would minimize conduction errors. In the previous studies, thermocouples, thermistors, and mercury-in-glass thermometers were used. In the study now being reported,[2] thermocouples and thermistors were used, but because of placement problems, and because a better calibration reference was needed, a platinum-resistance thermometer was used instead of a mercury-in-glass thermometer.

[2] Throughout this paper, the more substantive results are given not only in the British units now customary in this country, but also in the International System of Units (abbreviated as SI). This is done in recognition of the position of the USA as a signatory to the General Conference on Weights and Measures, which gave official status to the SI system of units in 1960. To assist readers interested in making use of the coherent system of SI units, the exact conversion factors used in this paper are:

Length	1 inch = 0.0254 meter.
Velocity	100 ft/min = 9.0508 meter/second
Temperature difference	1 deg F=5/9 deg C = 5/9 K (kelvin)

2. Description of Apparatus

The tests employed a well-insulated, round metal duct with an air-mixing device near the inlet. Air was drawn through the duct at velocities sufficiently high to produce turbulent flow. All temperature measurements were performed at a station seven duct diameters downstream of the mixing device. The duct walls were heated for a distance of 3.7 duct diameters upstream and 3.7 downstream of this station. A temperature boundary layer along the duct wall started at the leading edge of the heated section, and grew in thickness in the flow direction. At the test station, this boundary layer was still quite thin. The remainder of the volume of air was essentially isothermal so that the conduction of heat through the air to the temperature sensors was not significant. All temperature measurements at this station were made near the axis at the center of the isothermal volume of fluid. The magnitude of the radiation error was directly assessed by obtaining measurements with and without radiation shields and comparing them with measurements made with specially constructed reference sensors.

Two nearly identical thermocouples, two nearly identical thermistors, and the resistance thermometer comprised a probe which was part of a rigid assembly designed to prevent flexure of the leads and to minimize conduction losses. The probe was placed longitudinally in the center of the duct and parallel to the direction of the flow of moving air. Figure 1 shows the assembly consisting of the probe (A); a cage-like structure housing bare lead wires for minimizing conduction errors (B); a hollow, phenolic cylindrical structure (C), which served to thermally insulate the plastic tube carrying the leads through the duct wall and which was useful in determining if there were any conduction errors involved during testing (experiments performed to make this determination are described later); and a wooden cabinet (D), which housed an ice bath and a junction box. The junction box, which had gold-plated connectors to minimize corrosion, was used to connect the thermistor leads to the thermistor bridge in the instrument room which was remotely located. Wire leads to the measuring equipment in the instrument room for the thermocouples and the resistance thermometers were permanently connected to the assembly.

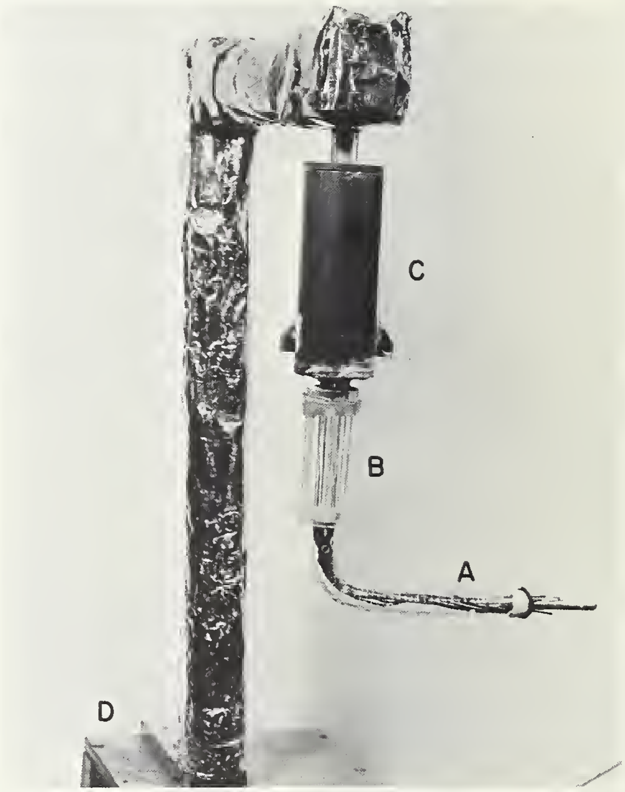

FIGURE 1. *The probe housing two thermocouples, two thermistors, and a resistance thermometer.*

The ice-bath for the thermocouples is housed in the cabinet in the lower portion of the figure. Conduction errors were minimized with the use of the cage-like structure housing the bare lead wires.

Details of the probe are shown in figure 2. The two thermocouples, the two thermistors, and the resistance thermometer were fixed in a rigid man-

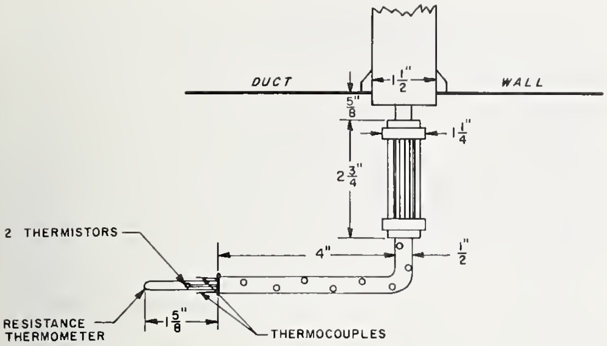

FIGURE 2. *Diagram of the probe-end showing the two thermocouples, one of the two thermistors, and the capsule-type platinum resistance thermometer.*

ner at the end of the probe, and the leads, insulated in vinyl plastic sheathing, were fixed rigidly through the center of thin-walled methyl methacrylate tubing bent at a right angle (fig. 1). Holes about 0.1 in diameter were placed in the tubing to allow the flow of air across the insulated lead wires thereby further reducing conduction and errors due to reradiation of heat from the plastic tubing to the wires (figs. 1 and 2).

The leads running from the probe to the ice-bath and the junction box in the assembly were rigidly fixed into the U-shaped methyl methacrylate tubing between (C) and (D) by filling the tubing completely with epoxy resin. This rigidization reduced cold-working of the wires which could cause a change in results from calibration to calibration. The tubing was insulated with sponge-rubber and with a reflective covering.

The thermocouples in the probe were of No. 30 B and S gage (0.010 in) Chromel P and constantan wires. Each junction was about ⅛ in long. All-copper switches were used in the electrical circuit of the thermocouple system. The ice bath consisted of two wells filled with oil inserted in an insulated Dewar flask containing slushy ice. The wells were immersed to a depth of more than 6 in in the ice, and the junctions were placed near the bottoms of the wells. This procedure was recommended by Caldwell [2]. The floating ice in the bath was maintained at a sufficient depth to extend below the bottoms of the wells at all times. The ice bath was stirred about every 3 hr. The use of Chromel P–constantan thermocouple wires further helped minimize conduction error because of their low thermal conductivity, which was about 6 Btu hr $^{-1}$ ft $^{-1}$ deg F^{-1} for chromel and about 13 Btu hr $^{-1}$ ft $^{-1}$ deg F^{-1} for constantan as compared copper which is about 200 Btu hr $^{-1}$ ft $^{-1}$ deg F^{-1}.

The wires connecting the assembly to the switch and to the potentiometer in the instrument room were copper. A precision-type laboratory potentiometer was used for measurment of voltage. It was capable of direct reading to within 1μV and of interpolation to within 0.1μV, corresponding to 0.03 deg F and 0.003 deg F, respectively, when Chromel P–constantan thermocouples are used.

Each of the two bead-type thermistors had a nominal resistance of 2000 Ω at 77 °F. Dimensional details of one of the thermistors are shown in figure 3. The two lead wires within the glass stem were made of untinned wire having a low thermal conductivity, and having a coefficient of expansion approximately equal to that for glass. According to the manufacturer, the "dissipation constant" in still air is 25 sec; beta [3] (a material constant) at 25 °C (77 °F) is 3465±175 K; and the resistance ratio, $\frac{R_o\ (0\ °C)}{R_o\ (50\ °C)}$ or $\frac{R_o\ (32\ °F)}{R_o\ (122\ °F)}$ is 7.1. The parameter R_o is the resistance of the thermistor measured when a low level of electric power, small enough so as not to heat it appreciably, is applied. The manufacturer advised that the thermistors supplied had been aged at elevated temperatures, a precaution which is regarded as necessary to impart stability. [3] A modified ratio bridge was used with the thermistors. The bridge was constructed so that the dial reading was nearly linearly related to the temperature of the air. [4] Shielded microphone cables were used to connect the wires from the junction box in the probe assembly to the thermistor switch, in the instrument room. Gold-plated connectors were used at the thermocouple selector switch.

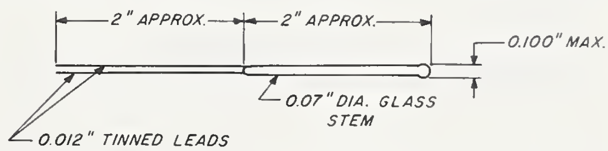

FIGURE 3. *Physical dimensions of each of the thermistors.*

A capsule-type platinum resistance thermometer 1.63 in long with a diameter of 0.25 in was used. The capsule was made of polished platinum. Four lead wires from the capsule were connected to long copper wires leading to the Mueller bridge in the instrument room. These four lead wires are needed in Mueller bridge measurements to compensate for effects in lead wire resistances. The bridge was capable of reading to the nearest 0.0001 Ω, corresponding to a temperature resolution of 0.002 deg F.

A schematic drawing of the apparatus is shown in figure 4. The test duct, 12 ft long, was made of brass, had a wall of ⅛ in thickness, and had a diameter of 10 in O.D. It was heated around the measuring section with electrical heating cables for a distance of 3 ft upstream and 3 ft downstream from the probe. The duct was insulated along its entire length. There was an access door at the top of the duct with an access mechanism for placing the probe in the duct. This door had

[3] Beta is approximately constant. It appears in the equation $R=R_o e^{\beta\left(\frac{1}{T}-\frac{1}{T_o}\right)}$ where T is any Kelvin temperature, and T_o is the temperature at which R_o was determined.

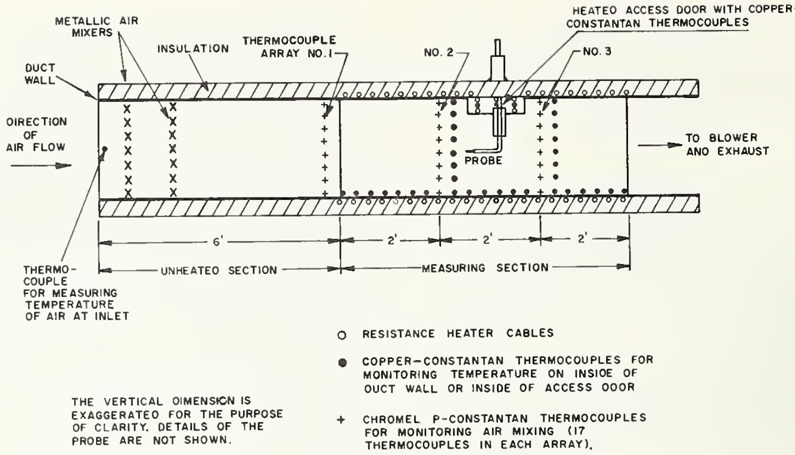

FIGURE 4. *Schematic diagram of duct and associated air-mixing, heating, and temperaturc-sensing equipment.*

a heating cable of its own. Copper-constantan thermocouples were placed in two rings around the inside surface of the duct, one upstream and one downstream from the probe, as well as on the inner surface of the duct along the bottom of the entire length of its measuring section, and on the bottom of the access door. These thermocouples were used to monitor the temperature of the duct wall.

The temperature of the air in the room and surrounding the duct was within 2 deg F of the temperature of the air at the intake to the duct. The air intake was from a large reservoir of air that had been held constant to within 0.15 °F for a period of at least 1 hr before each test. The air was exhausted from the duct to a remote part of the large air reservoir. The instrument room, remote from the room housing the duct, was maintained at about 75 °F throughout each test.

A concentric-louvered, metallic air-mixing device developed at the National Bureau of Standards [5] was used to insure thorough mixing of the inlet air. This resulted in a uniformity of air temperature at the entrance to the heated section. To observe the degree of temperature uniformity throughout a test, constant monitoring of air mixing took place using three arrays of 17 butt-welded Chromel P–constantan thermocouples in cross sectional areas in the duct. The butt-welded thermocouples were approximately 2 in from each other, and each one on the outer periphery of the array was approximately 1 in from the inside surface of the duct. One thermocouple was in the center. One array was upstream in the section of the duct that was unheated, another immediately upstream from the sensors in the heated section, and a third downstream, also in the heated section. No. 36 B and S gage wire (0.005 in diam) was used for the thermocouples. The use of the fine-gage, butt-welded thermocouple wires reduced conduction and radiation error. The flow was turbulent in the region close to the duct wall even at 300 fpm and the low time constant of the thermocouples caused difficulty in making the thermocouple readings in this region. This difficulty was overcome by the use of an integrating type digital voltmeter by which an accurate average microvolt value for each thermocouple in this region was obtained. Due to the multiplicity of thermocouples, a zone box was used along with a single, common reference junction in an ice bath. The circuitry for using a zone box wih Chromel P–constantan thermocouple is described by Roeser [6].

There were radiation and conduction errors within each array, but these were sufficiently small so that the arrays served as satisfactory indicators of air mixing and radial temperature gradients. Throughout the testing program, when there was a measurable difference in temperature between the moving air and the duct wall, there were low radial temperature gradients and almost no fluctuation in temperature in the region immediately surrounding the probe. Throughout the rest of the volume of the stream of moving air, the air exhibited temperature fluctuations in increasing magnitude and frequency in locations near the duct wall.

Reference sensors were used as a means for obtaining temperature values almost completely unaffected by radiation and conduction and for making comparisons with the values obtained with the probe. These consisted of three thermocouple junctions fabricated from No. 36 Chromel P–constantan wire supported by a plastic cage-like structure. The six lead wires were bare and were strung back and forth in the cage so that about 5 in of the wire was exposed to the moving air. This technique, together with use of fine wires, minimized conduction error. The three junctions were butt welded to minimize radiation error. The average of the three thermocouple readings was used for the reference value.

Details of the experimental program required that two different types of reference sensors be used. The first, used for the tests where the probes were shielded, fitted snugly into the inner of two 10-in-long concentric shields just upstream from the probe. This reference sensor and the concentric shields are shown in figure 5. The two shields were made of polished aluminum. The diameter of the inner shield was 2 in and that of the outer shield was 3 in. The second reference sensor, used for the tests where the probe was not shielded, fitted snugly into the inner of two 3-in-long concentric shields fabricated especially for the reference sensor. The sensor and its shields were placed immediately upstream from the probe. These are shown in figure 6. The diameter of the inner shield was 1 in and of the outer shield was 2 in. These small diameters were used to reduce radiation end effects. Both of the concentric shields were made of polished aluminum.

The effectiveness of the radiation shields for the reference sensors was determined by special tests and the errors were found to be very small but measurable. Details on how measurements and corrections for the small errors were made are given later.

FIGURE 5. *Large shield and the reference sensor used in the tests where the test probe was shielded.*

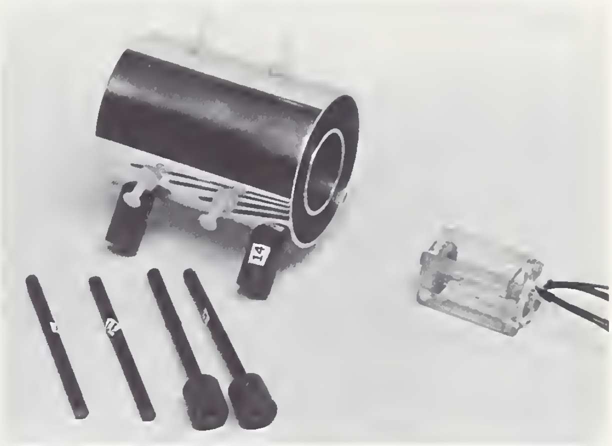

FIGURE 6. *Small shield and the reference sensor used in tests where the test probe was unshielded.* Removable legs for the shield are shown in lower left.

3. Calibration

The errors in uncalibrated temperature-sensing devices are usually determined by comparison of their indications with those of a secondary or primary standard whose errors have previously been analyzed. These comparisons are typically made in an apparatus in which there is minimum opportunity for heat transfer to or from the devices by radiation, conduction, or convection and in which the change of temperature with time is also minimized. An example is calibration of thermistors in a water bath whose temperature is close to the temperature of the room. In the present study the errors of several types of sensors were to be evaluated under conditions in which there was opportunity for heat transfer to or from the devices by radiation, convection, and conduction. In such a situation, a secondary or primary standard would also have unknown errors, so a simple comparison was no longer adequate.

Therefore, the following plan of attack was followed:

a. The platinum resistance thermometer used in the test probe was calibrated by the NBS Thermometry Laboratory, using the normal procedures described by Riddle [7].

b. Because of the well known stability of platinum resistance thermometers, the platinum resistance thermometer used in the test probe was used to calibrate the thermocouples and thermistors and also the two three-junction reference sensors in still air under isothermal conditions.

c. The magnitudes of small errors of the two three-junction reference sensors under nonisothermal conditions in the test duct were determined by comparing temperature indications when the junctions were aspirated at a velocity of 1400 fpm and when they were not aspirated.

d. The magnitudes of the larger errors of the thermocouples, thermistors, and the resistance thermometer in the probe were determined under nonisothermal conditions in the test duct for a range of air velocities by comparison with the calibrated reference sensors.

e. At the close of the program, the observed readings of the resistance thermometer in the probe were compared in still air with observed readings of another resistance thermometer calibrated by the NBS Thermometry laboratory. At the four temperatures within the range of temperatures of 75 to 80°F at which the comparison between the two resistance thermometers was made, there was less than 0.02 deg F (0.01 K) difference between the observed readings of the two thermometers.

The thermocouples, thermistors, and the large reference sensor were calibrated four times within a year, and the small reference sensor twice, one year apart. These sensors were calibrated in air, shielded from ambient temperatures by a large insulated Dewar flask. This flask is shown in figure 7. An insulated cover was over the flask during calibration.

FIGURE 7. *Calibration chamber for calibrating the thermistors, thermocouples, and the two reference sensors in still air.*

The changes in performance for the thermocouples, thermistors and the reference sensors between calibrations are shown in table 1. The changes listed are consistent with those shown in isothermal tests reported by Davis, Faison, and Achenbach [1].

Before each calibration in still air, the Dewar flask housing a probe or the reference sensor remained for at least 24 hr at an ambient temperature constant within ±0.06 deg F and usually within ±0.04 deg F. After the calibration started there was usually a small rise in temperature in the room due to the heat from the lights and from the observers. Full consideration was therefore given to errors which might have been caused by the order in which the thermistors or the thermocouples were read. Analysis showed that the contribution of self-heating of the resistance thermometer or the thermistors due to current flow was negligible.

When a reference sensor was calibrated, the cage-like structure was maintained at a center position in the flask so that the three No. 36 butt-welded Chromel-constantan thermocouple junctions were about ⅛ in from the end of the resistance thermometer. Figure 7 shows the reference sensor for the 10-in set of shields as it was placed inside the Dewar flask ready for insertion of the probe which housed the resistance thermometer.

The test probe with its three types of sensors, and the two reference sensors, were each calibrated as an assembly to avoid the problems of disassembly. These assemblies were calibrated in still air rather than water to avoid the need for insulating the sensors electrically.

When determining the magnitudes of the small errors in each reference sensor by the aspiration technique, the velocity of the air moving across the reference junctions within the inner shield was increased to 1400 fpm using a vacuum pump. Special adaptors were used for connecting the air-line from the inner shield to the vacuum pump. A comparison was made between aspirated and non-aspirated values at selected levels of temperature difference (Δt) between the duct wall and the moving air at the probe as measured by the resistance thermometer. Based on well-established theory [8, 9], calculations showed there was no appreciable error in the reference sensor due to radiation or conduction at a velocity of 1400 fpm, even for a Δt of 50 deg F.

This comparison showed that the error of the large reference sensor in the long 10-in set of shields reached a value of 0.08 °F when the difference in temperature between the duct wall and the moving air was 50 deg F and the air velocity was either 300 or 500 fpm. The errors of the small reference sensor in the small set of shields were considerably greater than for the large reference sensor under comparable conditions. Curves showing the errors determined in this manner, and used for corrections for both reference sensors, are shown in figure 8. A small uncertainty is indicated at the bottom of the curves for each reference sensor by a horizontal line across the figures at a distance about 0.04 deg F above the zero error line at the 0 °F point. For both reference sensors, the indicated temperatures when aspirated were 0.04 deg F lower than when unaspirated with no temperature difference between the duct wall and the moving air. This disparity is the reverse of what would be expected as a result of impact effects. While the cause is not known, it is probable that there was a change in the air mixing pattern within the shield when the air velocity was changed. Since the error involved was not due to radiation it was not considered in the corrections.

TABLE 1. *Change in performance of the sensors between calibrations (deg F.)*

Date of Calibration	Probe Sensors									Reference Sensors					
	Thermocouples No. 1 and 2 (Avg.)			Thermistor No. 1			Thermistor No. 2			Large			Small		
	75 °F	78 °F	80 °F	75 °F	78 °F	80 °F	75 °F	78 °F	80 °F	75 °F	78 °F	80 °F	75 °F	78 °F	80 °F
Aug., 1965															
	−.03	−.03	.00	−.03	.00	.00	.00	.00	.00	−.12	−.06	−.10			
Oct., 1965															
	+.03	+.03	.00	.00	−.03	−.03	−.03	−.03	.00	−.03	−.06	−.06			
Jan., 1966															
	−.03	−.03	−.03	.00	.00	+.03	.00	.00	.00	+.06	+.06	.00			
Oct., 1966															
Oct., 1965															
													.00	+.03	+.03
Oct., 1966															

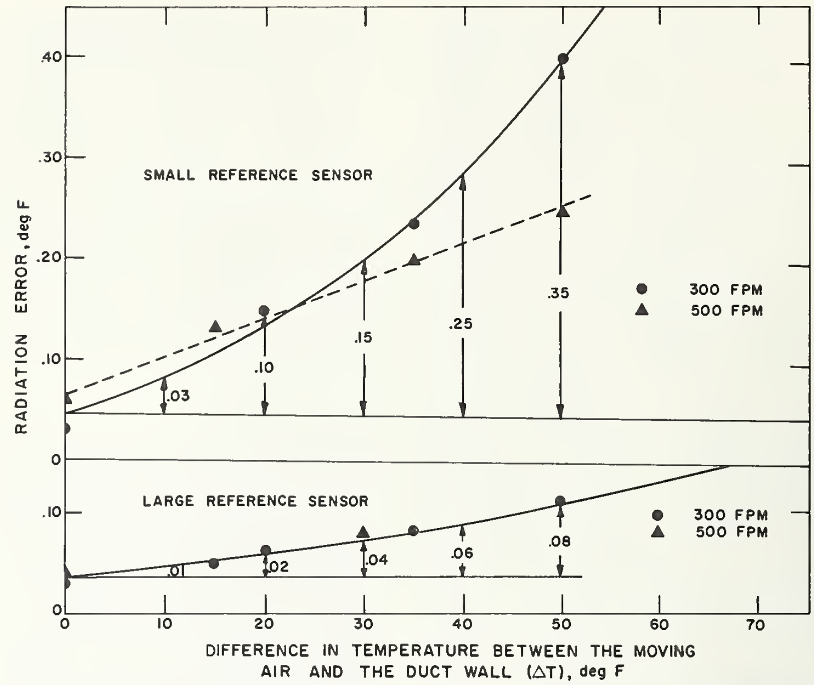

FIGURE 8. *Errors in the two reference sensors as a function of the difference in temperature between the duct wall and the air at the reference sensors.*

These errors were used for making corrections in calculations.

4. Method of Testing

Tests were performed at 300 and 500 fpm with and without shields around the probe. Tests at 1300 fpm were performed only without shields, because the theory and results from the tests at 300 and 500 fpm showed that the radiation error at 1300 fpm with shields would be almost nonexistent even for a Δt of 50 deg F. Tests for each condition were performed with none of the sensors aspirated, and during a continuous 12-hr period to reduce the effect of differences in ambient conditions, thereby facilitating better comparisons.

Before the design of the probe was fixed, calculations had been made to determine if conduction of heat from the duct wall along the wires was significant [9,10]. Before the tests, experimental verification was made. Hot metal, about 50 deg F hotter than the temperature of the duct wall, was applied suddenly in the hollow phenolic tube (designated as C on figure 1) to the plastic tube housing the lead wires. There was no indication of temperature change on any of the indicating instruments for the thermocouples, the thermistors, or the resistance thermometer. The same technique was used for the reference sensors. In each case there was no indication of temperature change.

All air velocity measurements were made with a pitot tube and a self-calibrating manometer which could be read to the nearest 0.01 in water gage.

Tests with the long metal shields around the probe were performed first. The sensors of the probe were not aspirated. The reference sensor assembly was placed in the end of the inner shield. Each test was performed at a selected level of velocity of 300 or 500 fpm. For these tests the difference in temperature (Δt) of the moving air and the duct wall was held at 0, 10, 20, 30, 40, or 50 deg F for a period long enough to assure steady-state conditions. The value of Δt was considered to be the difference between the reading of the resistance thermometer and the average of the readings of all the thermocouples in the rings around the duct, at the bottom, and on the access door. Steady-state conditions were obtained for each test, but no attempt was made to obtain values of Δt any closer than within 1 deg F of the preselected values. At each condition of velocity and temperature difference, 15 readings were taken for the thermocouples, the thermistors, and the resistance thermometers. The readings were 2 min apart.

Before taking the readings, readings of the thermocouples of the three arrays along the duct were taken to determine if the air mixing pattern was satisfactory. A satisfactory and randomly chosen cross-sectional temperature pattern from a test is shown in figure 9. This pattern was obtained during a test with Δt=40 deg F and with an air

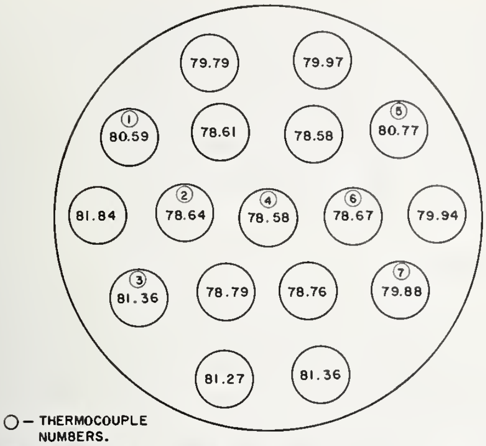

FIGURE 9. *Map of air-temperatures in Fahrenheit degrees of a cross-sectional area during a typical test when $\Delta t=40$ deg F.*
Data obtained from an array of butt-welded chromel constantan thermocouples fabricated from No. 36 wire (AWG). Array was immediately upstream from the probe.

velocity of 500 fpm. It was for the array of thermocouples immediately upstream from the probe. The cross-sectional temperatures, it will be noted, were essentially uniform in the central area for the seven thermocouples nearest to the center of the duct. Analyses of comparable data for the other two arrays along the length of the duct during the same test showed a similar and satisfactory pattern. This is illustrated in table 2, showing temperatures for selected corresponding positions in the arrays.

TABLE 2. *Air temperature for corresponding positions in the three arrays along the length of the duct, 500 fpm*

$\Delta t=40$ deg F, Duct wall temperature=119 °F, Inlet Air Temperature=78.3 °F

Position No. in Each Array	First Array (Upstream from heated section of duct)	Second Array (In heated section of duct, immediately upstream from probe)	Third Array (Downstream from probe in heated section of duct)
1	78. 34	80. 59	83. 97
2	78. 46	78. 64	79. 14
3	78. 37	81. 36	83. 99
4	78. 34	78. 58	78. 76
5	78. 43	80. 77	85. 30
6	78. 43	78. 67	79. 53
7	78. 46	79. 88	82. 31

The mixing was satisfactory for all tests. Comparison made of the pattern in figure 9 with two other determinations, made at the same station at 40 deg F Δt and at 500 fpm, showed that in each case the maximum difference between any of the seven center readings was less than 0.30 deg F. The difference between the average of these 7 readings and the center reading was always within 0.10 deg F. For the tests at 50 deg F Δt at the same velocity, the maximum difference between any of the seven readings was about 1.0 deg F. The difference between the average and the center was 0.7 deg F. For the tests performed at smaller values of Δt, the differences were considerably smaller.

The temperature of the inlet air coming into the duct was monitored using a copper-constantan thermocouple in conjunction with the digital voltmeter. There were unavoidable small cycles in the temperature of this inlet air, and to minimize any effect of these cycles, determination of the air pattern was made only at instances in time when that temperature was constant within 0.1 deg F. The mass in the metallic air mixers tended to dampen the cycles and help even more. The readings for the thermocouples in the arrays were taken in rapid succession.

After the tests with the 10-in shields were performed, tests without shielding around the probe but with small shields around the reference sensor were made at 300, 500 and 1300 fpm. The small reference sensor, in its special set of shields (fig. 6), was placed immediately upstream from the probe. The same test conditions as used for the tests with the 10-in shields were used. For the test at 1300 fpm it was not possible to obtain readings for $\Delta t=50$ deg F because of shortage of electrical power in the test facility.

The temperature of the moving air was steady near the axis of the duct; therefore it was possible to determine the readings of the fine-wire, butt-welded, thermocouples in the reference sensors with the manually operated potentiometer.

5. Results

The results of the studies are shown in figures 10 and 11. Figure 10 includes curves showing the effect of radiation when the three sensors were measuring the temperature of the moving air at 500 and 1300 fpm, and figure 11, curves showing the effect when the sensors were measuring this temperature at 300 fpm. For the unshielded sensors under the conditions of 1300 fpm (6.6 m/s) air velocity and a Δt of 50 deg F (28 K), the observed error was about 1 deg F (0.6 K). For 500 fpm (2.5 m/s) and 300 fpm (1.5 m/s), under the same test conditions, the error was about 3.0 deg F (1.65 K) and 3.8 deg F (2.1 K), respectively. When the sensors were shielded, at both 300 and 500 fpm and under the same test conditions, the error was less than 0.2 deg F (0.1 K).

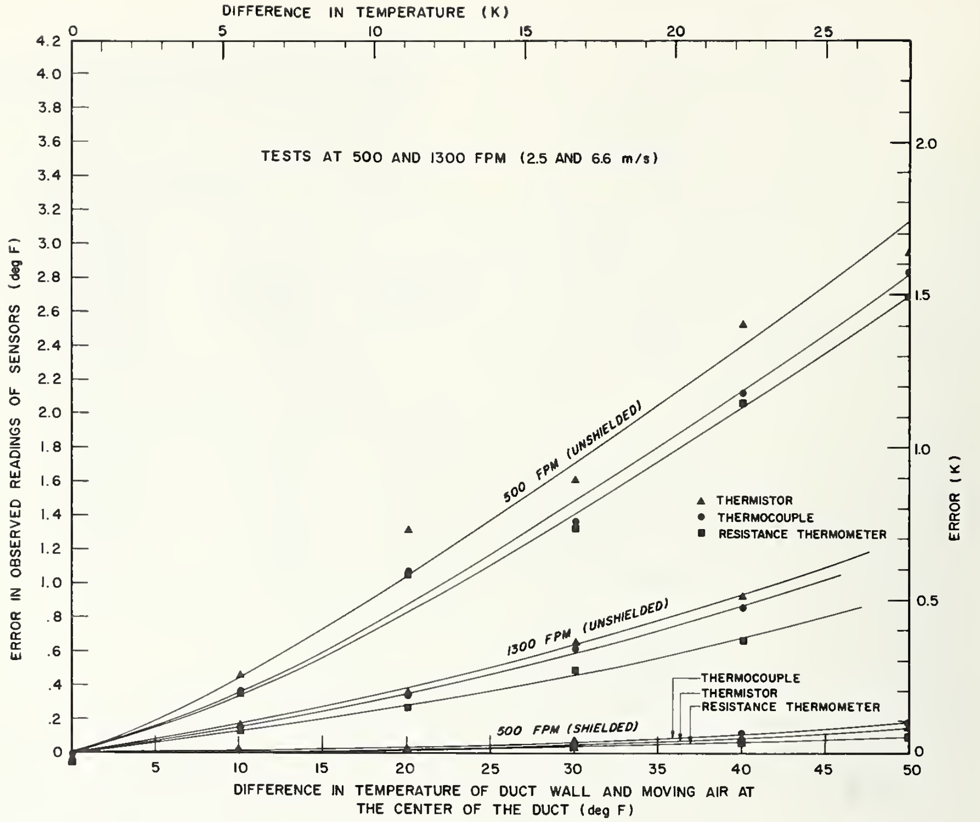

FIGURE 10. *Observed radiation error for the three types of sensors in the test probe, when used in air having velocities of 500 and 1300 fpm.*

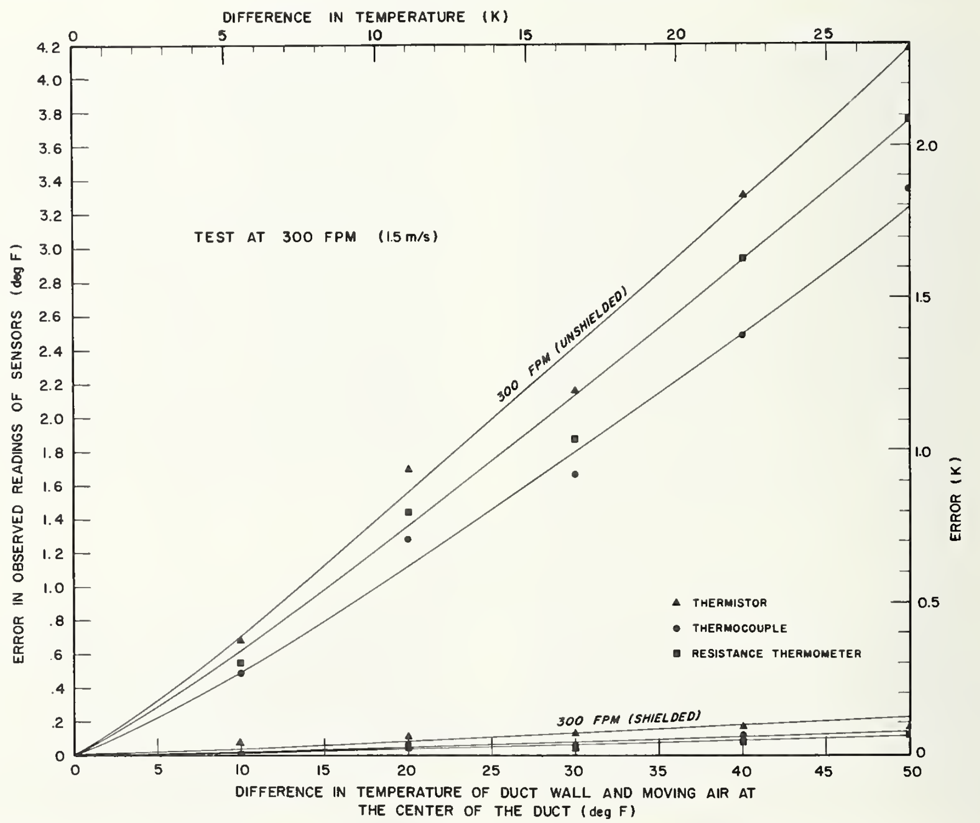

FIGURE 11. *Observed radiation error for the three types of sensors in the test probe, when used in air having a velocity of 300 fpm.*

The indicated radiation error was greater for the thermistors than for the other two types of sensors for all but one test condition. However, the indicated radiation errors for the thermocouples and the resistance thermometer change in magnitude relative to each other from one year to the next. The cause of the change is not understood, but it is probable that from the spacing on figures 10 and 11 between the thermistor curves and the resistance thermometer curves, and from the constancy of their relative positions, that the thermocouples had changed, not the thermistors or the resistance thermometer.

6. Errors in Measurement

Uncertainties occurring in the experimental work resulted in small errors in the observed results. For the tests where the probe was shielded, the possible error in experimental results was relatively large when compared to the radiation error reported. This uncertainty was principally due to the drift in observed values between calibrations for the thermocouple wire in the reference probes. Table 1, giving the change in performance of the probe sensors and the reference sensors, shows that the performance of the reference thermocouples sometimes changed 0.06 deg F between calibrations, and for two measurement temperatures changed -0.10 and -0.12 deg F, respectively. Another uncertainty was involved in using the aspiration technique on the reference sensors where the measured radiation error was 0.04 deg F at $\Delta t=0$.

It is possible that some of the experimental errors for the shielded probe could have been cumulative and could have totaled as much as 50 percent of the reported radiation error of 0.2 deg F at $\Delta t=50$ deg F. However, in view of the several possible sources of error it is more probable that there were compensating effects and that they totaled something less than 50 percent. Even so, a reported radiation error of 0.2 deg F at $\Delta t=50$ deg F with an experimental uncertainty of 50 percent is not serious for most laboratory measurements.

For the tests where the probe was not shielded, the possible error in experimental results was relatively small when compared to the radiation error reported. The same causes for experimental error occurred for these studies as for the studies when the probe was shielded, but the effect of cycling of the temperature of the air stream was more evident. Another contributing factor seemed to be the scatter of readings in the thermocouples on the duct which made it difficult to know the difference (Δt) between air temperature and duct surface temperature for a given test with an accuracy of better than 1 deg F. Because of the difficulty, a choice was made after testing to plot the curves of figures 10 and 11 using the preselected nominal values of Δt. These factors contributed to the dispersion of the plotted error values in figures 10 and 11.

7. Summary and Discussion

Results showed that the three types of sensors in the probe were materially affected by radiation. At 50 deg F (28 K) difference in temperature between the duct wall and the air at the center of the duct, the error for all three unshielded sensors due to radiation was about 3.8 deg F (2.1 K) at 300 fpm (1.5 m/s) 3.0 deg F (1.7 K) at 500 fpm (2.5 m/s). At 1300 fpm (6.6 m/s) the expected error with the sensors unshielded would be about 1 deg F (0.6 K). Radiation error for all three shielded sensors was less than 0.2 deg F (0.1 K) even at as low a velocity as 300 fpm (1.5 m/s) and for a Δt of 50 deg F (28 K).

There appeared to be little change in calibration of the thermistors during the period of two years in which the studies were made. The change in the thermocouples, including the reference thermocouple ranged from 0.0 to about 0.10 deg F (0.06 K). The change in calibration of the resistance thermometer during the period was not significant.

The use of Chromel P–constantan thermocouples has the advantage of a high $\frac{dE}{dT}$ and of low thermal conductivity. They were also found to be easy to use during fabrication. They were rugged despite their small diameter. The electrical resistance of Chromel P–constantan wires is high, however, and when used with a digital voltmeter, without a preamplifier of high input impedance, such resistance may cause significant error. The Chromel P and the constantan wires should be tested for inhomogeneities [11].

It is recommended that a shielded probe as described be used for measuring temperature of moving air with either thermocouples, thermistors, or a resistance thermometer when the temperature of the duct is 5 deg F (2.8 K) or more above or below the temperature of the moving air in the center of the duct. Any of the three sensors could be used with greater accuracy at low air velocities when aspirated in a shield. The investigator can determine the approximate degree of error involved from the use of the curves of figures 10 and 11. It is immaterial whether the duct wall is colder or hotter than the moving air. If colder, the same magnitude of error determined from the curves will apply but will have a negative sign.

Under conditions often occurring in a psychrometric calorimeter for measuring the capacity of air-conditioning equipment when the air velocity is 1300 fpm and $\Delta t=5$ deg F, the expected radiation error for unshielded sensors would be about 0.1 deg F. For 500 and 300 fpm, the error would be 0.2 deg F and 0.25 deg F, respectively. For all of these conditions the expected radiation error for shielded sensors is less than 0.1 deg F (0.06 K). Under the test conditions that prevail in the testing of air-conditioners and heat pumps in laboratories, it should be possible to reduce the total error in temperature measurement of the moving air to about 0.2 deg F (0.1 K) by a combination of suitable air mixers, duct insulation, radiation shields and calibration techniques. This value is in agreement with the value recommended by Davis, Faison, and Achenbach [1] for Temperature Measuring Standards.

If all other conditions remained the same, increasing the diameter of the test duct beyond the 10 in size used for this study would decrease the magnitude of the radiation errors of a shielded probe somewhat because of the smaller radiation effects through the open ends of the shields, but would have very little effect on the errors of an unshielded probe. The curves for the shielded condition are applicable only if shields of the same material and low temperature-emissivity characteristics are used. A probe fabricated with material having a lower emissivity than methyl methacrylate, which has an emissivity [4] of about 0.7 to 0.9, or one which is wrapped with a covering of reflective foil, would have a smaller radiation error when used as an unshielded probe. In an actual application, the temperature sensor would probably consist of a single element of considerably smaller diameter than the entire probe used for the study. Such an element would probably have a somewhat more favorable relationship between radiation heat gain and convection heat loss than the test probe. Presumably individual sensors could be designed which have no more error than the reference sensors. It is important that the design of a temperature-sensing probe incorporate principles for minimizing conduction errors similar to those used in this investigation.

Appreciation is expressed to Messrs. Thomas K. Faison, Walter M. Ellis, and Jesse Dungan of the NBS staff for their assistance in performing the tests and in difficult fabrication of some of the pieces of equipment.

[4] As determined from materials such as paints which have similar radiation characteristics at the temperatures under consideration.

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